Design of an Integrated Inductor with Magnetic Core for Micro-Converter DC-DC Application

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This paper presents a design procedure of an integrated inductor with a magnetic core for power converters. This procedure considerably reduces design time and effort. The proposed design procedure is verified by the development of an inductor model dedicated to the monolithic integration of DC-DC converters for portable applications. The numerical simulation based on the FEM (finite elements method) shows that 3D modeling of the integrated inductor allows better estimation of the electrical parameters of the desired inductor. The optimization of the electrical parameter values is based on the numerical analysis of the influence of the geometric parameters on the electrical characteristics of the inductor. Using the VHDL-AMS language, implementation of the integrated inductor in a micro Buck converter demonstrate that simulation results present a very promising approach for the monolithic integration of DC-DC converters.

Keywords: Integration, Magnetic core, Integrated inductor, 3D-FEM, DC-DC converter

1. INTRODUCTION

Recent research works in the area of power electronics have mainly focused on the integration system in order to improve the performance of converters in terms of efficiency, compactness, and reliability.

The integration of the different components of a static converter is actually the main challenge in the area of power electronics. Indeed, considering the developments of distributed architectures or ‘System-On-Chip’, new techniques must be developed to reduce the size of power converters and achieve greater efficiency. Although much progress has been made in this area, some technological limits prevent the achievement of smaller components. Often, inductors occupy a much larger part of the chip surface than the active components. Thus, monolithic integrated inductors are urgently needed to reduce energy conversion losses.

Several works have been dedicated to inductors integrated with silicon substrates for power conversion [1-4]. This causes several forms of losses that affect the performance of the inductors [5]. Virtual prototypes need to be fabricated before manufacturing, in order to reduce the manufacturing cost and to increase the reliability of the designed circuits. Modeling and simulation are essential in designing integrated inductors on silicon for power conversion.

The first part of the paper describes the design procedure of integrated inductors with a magnetic core. The second part discusses the modeling and simulation of the inductor in a general approach tending towards the full integration of small power systems such as those designed for mobile phones. Then, the influence of various parameters such as the operating frequency, the spacing between the coils, the number of coils, and the thickness of the magnetic core are analyzed in detail by simulations with the 3D FEM (finite element method) in order to find the optimal settings. Finally, an application using the integrated inductor is described.

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2. DESCRIPTION OF THE INTEGRATED INDUCTOR

2.1 Inductor design procedure

The design of a power micro-inductor depends on the form of coils and the magnetic core, including the inductance value, the resistance, the efficiency, the size, and the manufacturing process.

Figure 1 illustrates the procedure of the proposed design. First, the specifications and requirements of the component’s design must be selected (inductance value \(L\), operating frequency \(f_{sw}\), current magnitude \(I_{pk}\), and the minimum quality factor \(Q_{L_{min}}\)). Second, the best geometric form must be chosen, which allows a high inductance value to be obtained in an occupied area and facilitates manufacturing. In the third step, the best materials to use for the realization of the integrated inductor must be chosen (conductive, magnetic, and dielectric materials). Then, considering these specifications, we can calculate the geometric parameters of the inductor (number of coils \(N\), spacing between coils \(W\), and height of coil \(t_w\) ...). A simulation is then carried out to extract the technological parameters of the inductor. If the results are satisfactory and the design requirements have been considered, the inductor can be realized. If not, the inductor design parameters must be changed.

By using this procedure, the design time and effort is considerably reduced.

2.2 Choice of the geometry

The selection of the form of inductor is the first important choice for the realization process of an inductor. In the literature dedicated to the integrated inductor, three types of inductors are presented: solenoid inductors, serpentine inductors, and spiral inductors.

In practice, the most commonly used type of inductor is the spiral type. The advantage of this inductor lies in its manufacturing ease and performance [6]. Indeed, a higher ratio of inductance is obtained with this inductor type due to the area occupied. For these reasons, a spiral inductor is selected for study in this work.

2.3 Structure of the proposed inductor

The inductors studied in this work are generally becoming miniaturized and are used for the monolithic integration of low power systems. The application concerned is used for energy conversion, particularly the DC-DC conversion for portable electronic devices. The inductor in the power conversion circuit is used primarily to store energy, and requires a high inductance value. To meet these requirements, an inductor with a magnetic core is used. The proposed inductor has two layers of magnetic material, the structure of which is specified in Fig. 2.

This two-layer structure is a “sandwich” structure which comprises a winding surrounded by two magnetic layers, one below and the other above the spiral.

Among the advantages of this structure is that it allows the increase of the inductance and quality factor values. In addition, at the given inductance, it allows minimization of the component surface and the manufacturing cost is therefore reduced. The presence of magnetic material on either side of the spiral offers magnetic shielding for the inductor.

2.4. Magnetic material

The use of a magnetic core in an inductor allows an increase in the value of its inductance, enabling channeling of the magnetic flux and the storage of energy. The optimum characteristics of the material constituting this core include a high relative permeability to a significant increase of the inductance, a level of induction saturation, and a high electrical resistivity in order to limit the iron losses by eddy currents. It should be noted that no material is perfect. Thus, a trade-off between these material characteristics should always be sought.

In order to realize inductive components in the domain of low power integrated systems, ferrite NiZn was selected.

In the literature [7], the magnetic core material used in manufacturing the integrated inductor is a composite of ferrite powder of NiZn. In fact, NiZn is a very important material used in electronic devices suitable for high frequency applications because of their high electrical resistivity, chemical stability, and good electromagnetic properties [8].

In addition, due to the properties of this non-conductive composite, it’s not necessary to implement isolation material between core, coils, and substrate.

The NiZn material of the magnetic core is characterized by a relative permeability \(\mu_r = 8\) and a magnetic field saturation \(B_{sat}\) equal to 0.2 T.
2.5 Conductor material

In the literature, the main conductor materials used to build the coil are Au, Al, and Cu [9]. Among these materials, Al presents the highest resistivity. Meanwhile, Au has the lowest resistivity and good resistance to oxidation. However, its disadvantage is its very high cost. Cu is the most commonly used material in the realization of inductors, actuators, and integrated transformers due to its attractive electrical properties. Thus, we selected Cu as the material used in our design procedure.

2.6 Analysis method

Owing to the complexity of integro-differential equation systems, an approximate solution is not easily found. In order to find a solution, numerical methods such as the finite element method, the finite volume method, the finite difference method, and the method of moments need to be used in the resolution [10].

The FEM (finite element method) is frequently considered among the most powerful and flexible numerical methods employing electromagnetism [11].

This FEM subdivides a large problem into smaller and simpler parts called finite elements [12]. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem.

By correctly discretizing the problem, our irregular structure could be analyzed. Our analysis mainly focuses on the estimation of the inductor values, the quality factor Q, and the internal resistance.

In this work, the three-dimensional finite element method (3D-FEM) is used based on the numerical resolution of the set of Maxwell’s equations. These equations are solved based on the discretization of the structure to be simulated.

3. 3D SIMULATION OF THE INTEGRATED INDUCTOR

The simulation results are presented using the form of S-parameters. The S parameters are then converted into Y parameters by equations (1), (2), and (3) [13]:

\[
Y_{11} = \frac{(1 + S_{12})(1 + S_{21}) + S_{12}S_{21}}{(1 + S_{12})(1 + S_{21}) - S_{12}S_{21}}
\]

(1)

\[
Y_{12} = \frac{-2S_{12}}{(1 + S_{12})(1 + S_{21}) - S_{12}S_{21}}
\]

(2)

\[
Y_{22} = \frac{(1 - S_{12})(1 - S_{21}) + S_{12}S_{21}}{(1 + S_{12})(1 + S_{21}) - S_{12}S_{21}}
\]

(3)

The equivalent circuit parameters \( L_s \), \( R_s \), and \( Q \) are calculated by equations (4), (5), and (6) from the theory of the inductor equivalent circuit.

\[
L_s = \frac{1}{2\pi f} \text{Img} \left( \frac{1}{Y_{11}} \right)
\]

(4)

\[
R_s = \text{real} \left( \frac{1}{Y_{11}} \right)
\]

(5)

\[
Q = \frac{\text{Img} \left( \frac{1}{Y_{11}} \right)}{\text{real} \left( \frac{1}{Y_{11}} \right)}
\]

(6)

Where \( L_s \), \( R_s \), and \( Q \) are the inductance value, resistance, and quality factor of the spiral inductor, respectively. These s-parameters could be used to produce electrical simulations, thus accelerating the circuit design.

A series of electromagnetic simulations was performed to study the influence of different geometric parameters on the value of the inductance and to select the optimal parameters.

3.1 Influence of the geometrical parameters on the inductor

By considering the electric and magnetic characteristics of the selected material, the geometric constraints of the component are studied. These geometrical constraints are the relationships of the operating frequency, the number of coils, and the space between them with the inductance value, the quality factor, and the amount of magnetic energy stored.

The influence of the inductor geometric parameters (number of coils, the space between coils, and magnetic core thickness) on the value of the inductance and quality factor is examined as follows.

The geometric parameters of the studied inductor are presented in Table 1. These geometric parameters of the inductor are selected for use in an integrated power converter.

Several electromagnetic simulations were established to study the influence of the space between the coils on the inductor value and the quality factor.

A variation of the spacing between the numbers of fixed coils is accomplished. The simulation results are presented in Figs. 3 and 4 for different inter-coil values with the number of coils equal to 10.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of winding ( t_w )</td>
<td>200 μm</td>
</tr>
<tr>
<td>Width of winding ( W )</td>
<td>60 μm</td>
</tr>
<tr>
<td>Inner diameter ( d_{in} )</td>
<td>300 μμm</td>
</tr>
<tr>
<td>Thickness of core ( t_c )</td>
<td>200 μμm</td>
</tr>
</tbody>
</table>

Table 1. Geometric parameters of the inductor.

Fig. 3. Quality factor, \( Q \) as a function of the spacing between windings, \( S \).
By increasing the spacing between the coils, the total length and area of the magnetic flux increase. The values of $L$ and $Q$ also increase. In addition, the large surface area causes an increase in the parasitic capacitance of the inductor and a decrease in the resonance frequency.

A series of electromagnetic simulations was established in order to study the influence of the number of coils on the values of inductance and quality factor with a constant spacing between the coils.

According to the results presented in Figs. 5 and 6, the increase of the number of coils leads to an increase in the values of the inductor, the quality factor and the surface area, but also the associated conduction resistance. The number of coils in the inductor accentuates the capacitive effects, such as the inter-coil capacitive effect, the influence of which appears with the increasing frequency.

To study the influence of the magnetic layer on the inductance value, simulations were performed by varying the thickness of the magnetic material from 50 μm to 200 μm.

Figure 7 illustrates the significant increase of the inductance value with the magnetic core thickness. The use of the magnetic core allows the inductance value to be multiplied towards a value of $\mu_r$ compared with an inductor without a core.

### 3.2 Influence of the operating frequency on the inductor

The inductance value and the quality factor based on the operating frequency of the studied inductor with the number of turns, $N = 10$, and a space between the windings equal to 40 μm are given in Fig. 8.

It is known that the switching frequency of the DC-DC converters of order 1 to 10 MHz are used in the design of portable electronic applications [14] that require an inductance value from 0.3 to 2 μH.

For a switching frequency of 6 MHz of a synchronous buck converter DC-DC, the choice of the inductance value from Fig. 8 leads to a value equal to 357 nH. This enables a quality factor, $Q$, of the order of 10.6 to be obtained. Moreover, the operating frequency affects the inductor’s series resistance as shown in Fig. 9, which is equal to 1.25 $\Omega$ for a switching frequency of 6 MHz.

A comparative study was carried out of the simulation results found by 3D numerical simulation and the results in the experimental work by M. Wang [15]. Taking into account the same conditions for measurements and simulations, a good agreement
was obtained between the simulation results of our modulated structure and the results of the experimental work [15] as shown in Fig. 10.

4. BUCK CONVERTER APPLICATION

The circuit of the synchronous buck converter shown in Fig. 11 is used to evaluate the performance of the integrated inductor. This topology of the converter is chosen because it provides better performance since it does not require an isolation transformer. The inductor we intend to integrate will be sized for this type of application.

In the simulation, the following values of the converter’s electrical characteristics are used:

- Input voltage $V_{\text{in}} = 3.3\, \text{V}$
- Output voltage $V_{\text{out}} = 1.8\, \text{V}$
- Output current $I_{\text{out}} = 0.5\, \text{A}$
- Operating frequency $f_{\text{sw}} = 6\, \text{MHz}$

The level of current and voltage used are relatively low in order to perform a monolithic integration of the converter.

To perform efficient electrical simulations, the multi-physical language VHDL-AMS was used with the SystemVision simulation tool from Mentor Graphics. This requires having the appropriate analytical models of each component of our converter.

While power MOSFETs (metal-oxide semiconductor field-effect transistors) are typically used in high power converters [16,17], they are not suitable for integrated converters due to the medium voltage and power ratings [18]. Therefore, CMOS (complementary metal-oxide semiconductor) transistors are used in integrated DC-DC converters.

An analytical model of the MOSFET implemented in VHDL-AMS is considered.

For inductor $L$, the model studied in the first part is used. The results obtained by the numerical simulator are extracted and used for the circuit simulator.

The output current simulated at a switching frequency of 6 MHz is shown in Fig. 12. It is observed that the output current is constant, and the mode is transient during the first few microseconds. The converter delivers an output current of about 450 mA. In addition, a similar observation is noticed for output volt-

![Fig. 11. Schematic diagram of the Buck converter.](image)

![Fig. 12. Output current waveform.](image)

![Fig. 13. Output voltage waveform.](image)
age as shown in Fig. 13. It is also important to note that the input voltage of 3.6 V is lowered to 1.8 V. The waveform current across the inductor terminals shown in Fig. 14 never crosses the zero-value. Therefore, the continuous conduction mode is respected.

Influence of the cyclic ratio

The variation of the output voltage with the cyclic ratio is an important characteristic of the step-down voltage converter. The output voltage of the down converter with the integrated inductor is shown in Fig. 15 for a switching frequency of about 6 MHz. It can be seen that the variation of the output voltage with the cyclic ratio is almost linear, which indicates that the operation is in the continuous mode.

5. CONCLUSIONS

In this paper, we proposed an integrated inductor design process with a magnetic core. Using the developed procedure, we demonstrated that the value of the inductor, the quality factor, and the size of the inductor could be predicted prior to manufacturing. Then, the influence of various parameters such as the operating frequency, the space between the turns, the number of turns, and the magnetic core thickness were analyzed in detail based on 3D simulations using the FEM (finite element method) to determine the optimal geometrical parameters of the inductor. The efficiency study of the integrated inductor in an application of the energy conversion was established. The desired value of the output voltage was also obtained from the simulation of the DC-DC buck converter microwave. The results show that the developed structure of the inductor is a very promising approach for the monolithic integration of DC-DC converters.

REFERENCES